UPPER-LEVEL STRUCTURE OF THE FORMATIVE TROPICAL CYCLONE

ROBERT W. FETT*, Major, USAF

AWS Member, National Weather Satellite Center, Weather Bureau, Washington, D.C.

ABSTRACT

In a survey of examples of formative tropical cyclones viewed by the TIROS satellite, and a comparison of many of these views with surface, upper-air, and time and space-section analyses, it is found that the upper-level structure of the formative cyclone of moderate intensity is grossly similar to that of the storm at maturity. Common features in most examples studied include: (1) an upper-level trough or shear line which preceded the low-level trough and which moved with the storm system; and (2) an upper-level ridge or anticyclone which was generally superimposed over the convective area east of the lower-level trough or vortex. As has been found with the mature storm, strong subsidence occurred under the upper trough and coincided with a cloudiness minimum area in advance of the major convective cloudiness and west of the trough axis. Upward vertical motion with heavy convective activity was suggested under the upper-level ridge or anticyclone to the rear of the lower-level trough. Several examples depict these features and demonstrate changes that occurred as the storms passed individual stations. The TIROS photos were invaluable in this study as a source of additional data for confirming the distribution and type of cloudiness, for implying flow patterns at upper and lower levels, and for providing the basis for reasonable estimates of the stage of development of the entire system. It is concluded that an easterly wave model incorporating an upper-level trough and ridge or anticyclone as integral features of the moving system is one which describes most adequately the majority of observations concerning formative tropical cyclones of moderate intensity and is one which is especially satisfying in terms of fulfilling the various theoretical and physical considerations.

1. INTRODUCTION

Much confusion has prevailed since the launching of TIROS I in attempts to relate suspected formative tropical cyclones [1] to prevailing synoptic conditions. The primary reason for this has been the sparcity of data over the areas of storm formation. The lack of a universally accepted model has also contributed to this confusion. Sadler [9] in particular, has been outspoken in his criticism of the classical easterly wave concept and has emphasized instead, the formation of vortices in (1) the low-level monsoonal trough and (2) the upper-tropospheric trough, without invoking an easterly wave type beginning in either case. The apparent formation of a tropical storm from an upper-level vortex that gradually induced a trough in the lower levels has been described by Frank [4]. However, the lack of a really definitive upper-wind network detracts somewhat from the conclusiveness of his study, and efforts to find and document good examples of similar development have not been fruitful. A physically plausible mechanism which would permit an upper-level trough to produce such a development is also lacking. More recently Merritt [6] has rallied to the defense of the easterly wave concept as originally defined by Riehl [8]. At the same time Merritt admits the possibility of induced waves from the more intense upper-level disturbances, and he further proposes a new, more general, category of "easterly perturbations" which may include vortices at various levels.

Fett [3] described the typical development of a tropical cyclone based on changes in appearance of the satellite-observed cloudy area associated with the system. Figure 1 shows the model development diagrammatically, and figure 2 shows typical examples viewed by TIROS. This descriptive model has been used operationally by the U.S. Weather Bureau since July 1964 in the identification and location of formative storms with generally good results. In an attempt to document the model more adequately additional examples were gathered and related to the conventional data available. The sample included tropical cyclones of all intensities up to and including newly formed tropical storms. The primary basis for selection of the examples considered was simply that enhanced convection exist over the ocean in the Tropics and that the area of enhanced convection be reasonably independent of other cloudiness such as that of the Inter-

*Now on assignment with Detachment 2, 30th Weather Squadron, Air Weather Service.

[1] The following definitions of tropical cyclone terms adopted from Dunn and Miller [1] are used in this paper:

Tropical disturbance—Rotary circulation slight or absent on the surface but possibly better developed aloft. There are no closed surface isobars and no strong winds. This type of disturbance is common throughout the Tropics.

Tropical depression—One or more closed surface isobars. Wind force equal or less than Beaufort force 7 (32–33 kt.).

Tropical storm—Closed isobars, wind force more than Beaufort force 7 (34–63 kt.).

Hurricane or typhoon—Wind force Beaufort 12 (64 kt.).

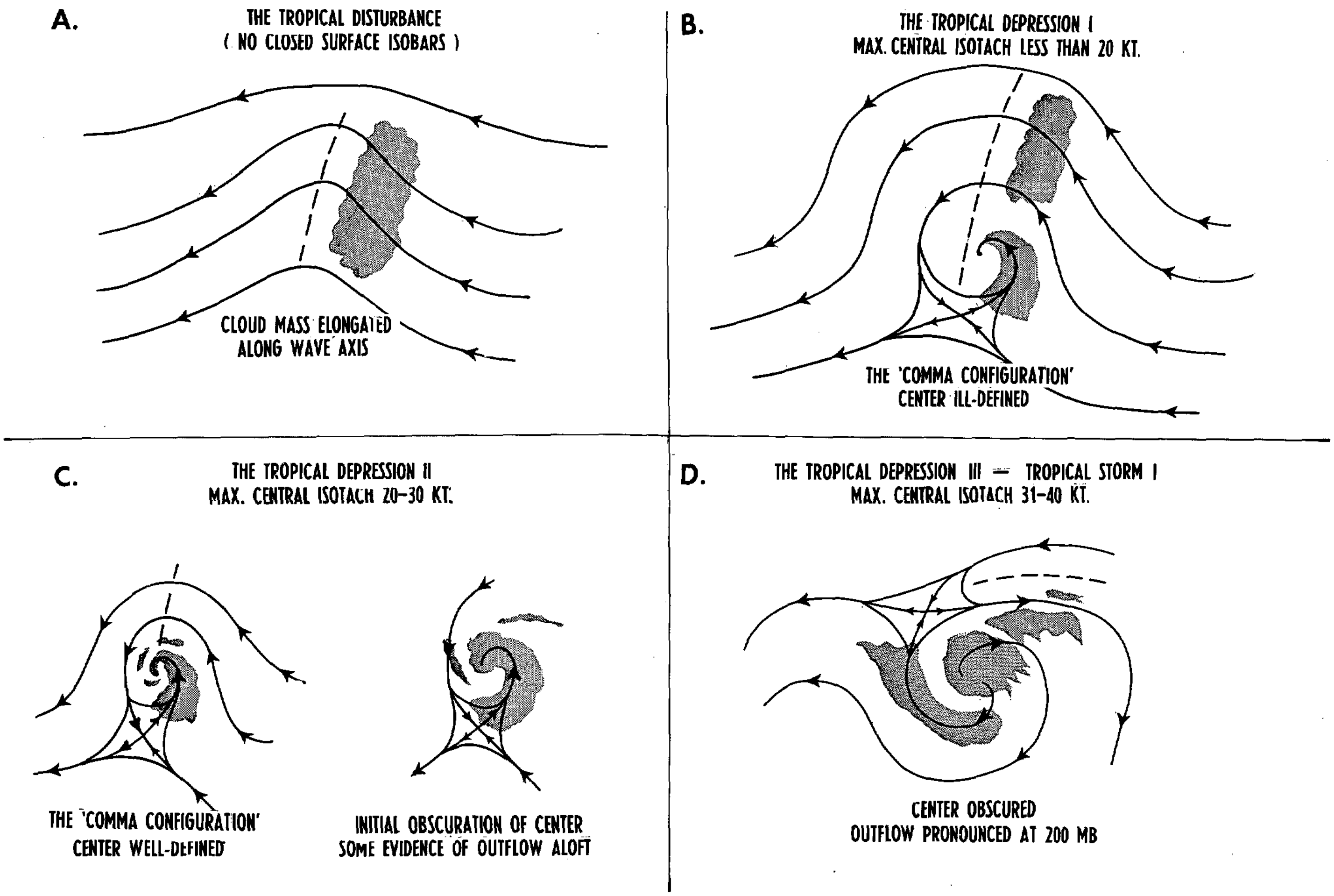

FIGURE 1.—A model describing the cloudiness distribution associated with the formative stages of tropical cyclone development. The model applies to formative tropical cyclones of the Northern Hemisphere embedded in easterly flow. In stages A, B, and C, the typical gradient wind streamline pattern is superimposed over the shaded TIROS-observed cloudy areas. In stage D, the typical 200-mb. streamline pattern is shown (See [6].).

tropical Convergence (ITC). At least three questions were applied to each of the examples considered: (1) Does the picture provide a good example of an upper-level vortex such as Sadler [9] described? (2) Is there an upper-level trough apparent in the conventional analyses that joins continuously to a lower-level trough? (3) How well is the example related to the classical easterly wave model depicted by Riehl [8]? Data were inadequate to provide a definitive answer in every example, but from the large number considered [2] a pattern clearly emerged:

(1) Most cyclones were preceded by an upper-level trough and had an upper-level ridge or anticyclone superimposed over the convective area east of the lower-level trough. The upper trough and ridge or anticyclone moved with the storm system.

[2] The initial sample included over 200 cases viewed by TIROS. A large number of these examples, however, were located in data-void areas where further documentation was impossible to obtain or only partial in nature.

(2) The upper-level trough in most instances did not appear to be connected to the lower-level trough.

(3) Riehl's model was generally applicable. However, the upper-level structure of the easterly wave was not emphasized in his presentation. The pattern most commonly found in the present study corresponded roughly to the phase reversal with height that he described when "an upper trough overlies the surface ridge and an upper ridge overlies the surface trough" ([8], p. 222). A notable difference, however, was that this phase reversal was not complete in the samples studied. The upper ridge or anticyclone was most commonly centered over the convective area *east* of the low-level trough—a position, hydrostatically, most reasonable (See section 5).

Examples demonstrating salient features of some of the cyclones viewed by TIROS followed by a brief discussion concerning physical plausibility constitute the remainder of this paper.

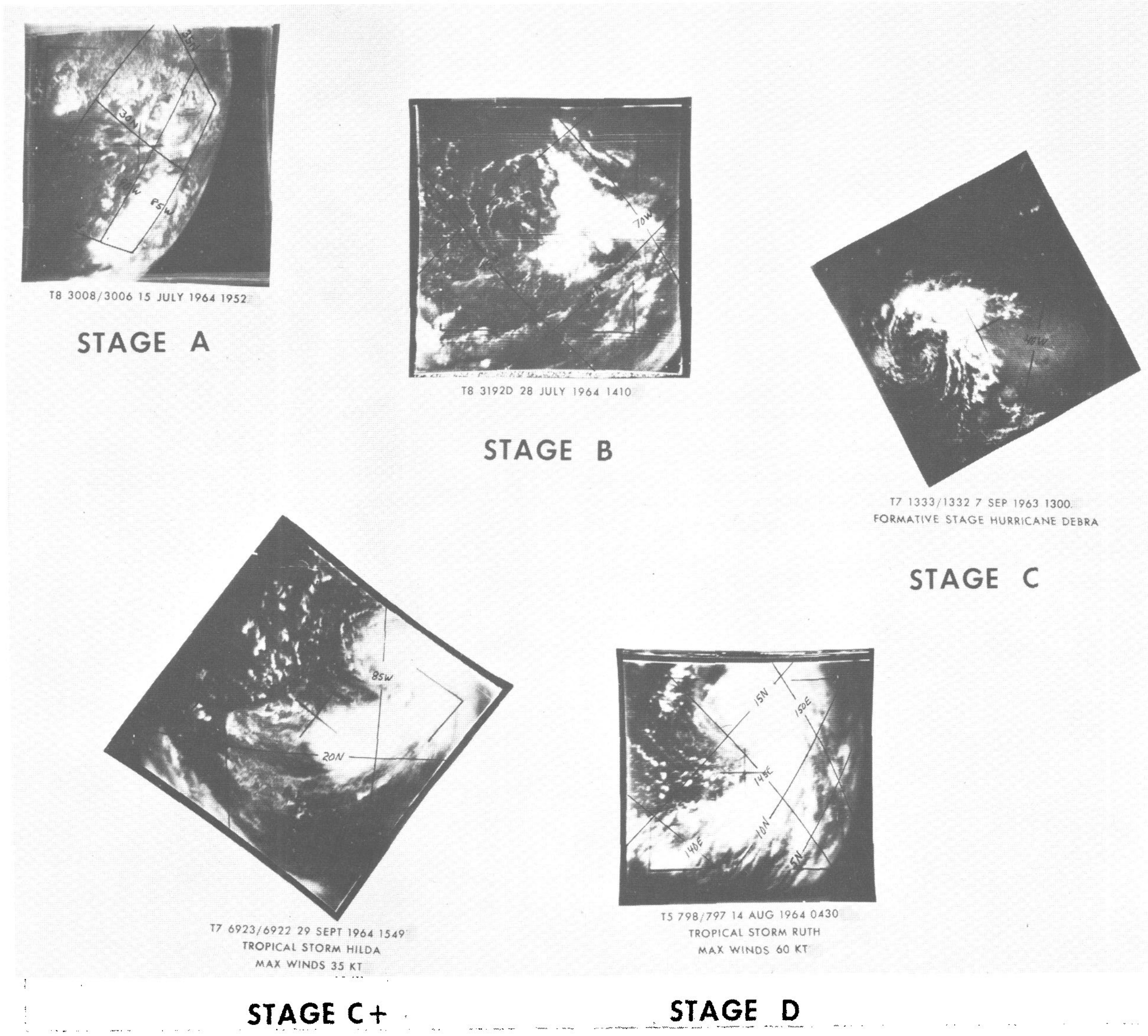

FIGURE 2.—Typical examples of the formative stages of tropical cyclone development viewed by TIROS.

2. GUATEMALAN STORM EXAMPLE

On September 27, 1962, TIROS VI photographed a vortex approximately 300 mi. east of the Lesser Antilles. This vortex could be tracked by satellite and conventional data for the next 7 days until it finally moved over Guatemala on October 3 and 4 [5]. Figure 3 shows the track of the storm in relationship to an upper shear line which moved westward as the storm progressed in the same direction.[3] Throughout the period an upper anticyclone was generally superimposed over the surface Low. On two occasions the shear line was observed to fracture from separate mid-latitude troughs that extended into the Caribbean. Figure 4 shows TIROS V views of the depression on October 1, 1962. The center of circulation of the system appears in the break near 14° N., 78° W., and the depression has an appearance conforming to a Fett Stage C classification (figs. 1 and 2).

Figure 5 shows the surface and 200-mb. analyses depicting conditions 3 hr. before the TIROS pictures. Of notable interest is the upper-level trough which preceded the depression. It is this typical close proximity of the upper trough to the depression area which at first glance suggests a causal relationship. In the absence of a definitive upper wind network an erroneous conclusion could easily be drawn. Figure 6, a time-section for Plesman, Curaçao (Station 988, near 12° N., 69° W.), however, reveals that the upper trough could not be traced below the 300-mb. level and that it was not connected to the lower-level trough, which sloped upward toward the east rather than toward the west.

[3] See also similar examples of shear-line movement in relationship to positions of mature storms [2].

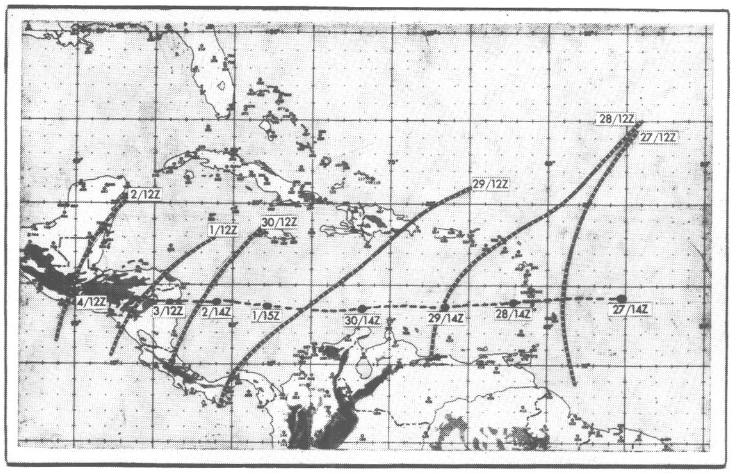

FIGURE 3.—Progressive 24-hr. positions of a shear line near the 200-mb. level associated with the Guatemalan storm. The track of the storm as determined from satellite and conventional analyses is shown in relationship to the progressive locations of the shear line.

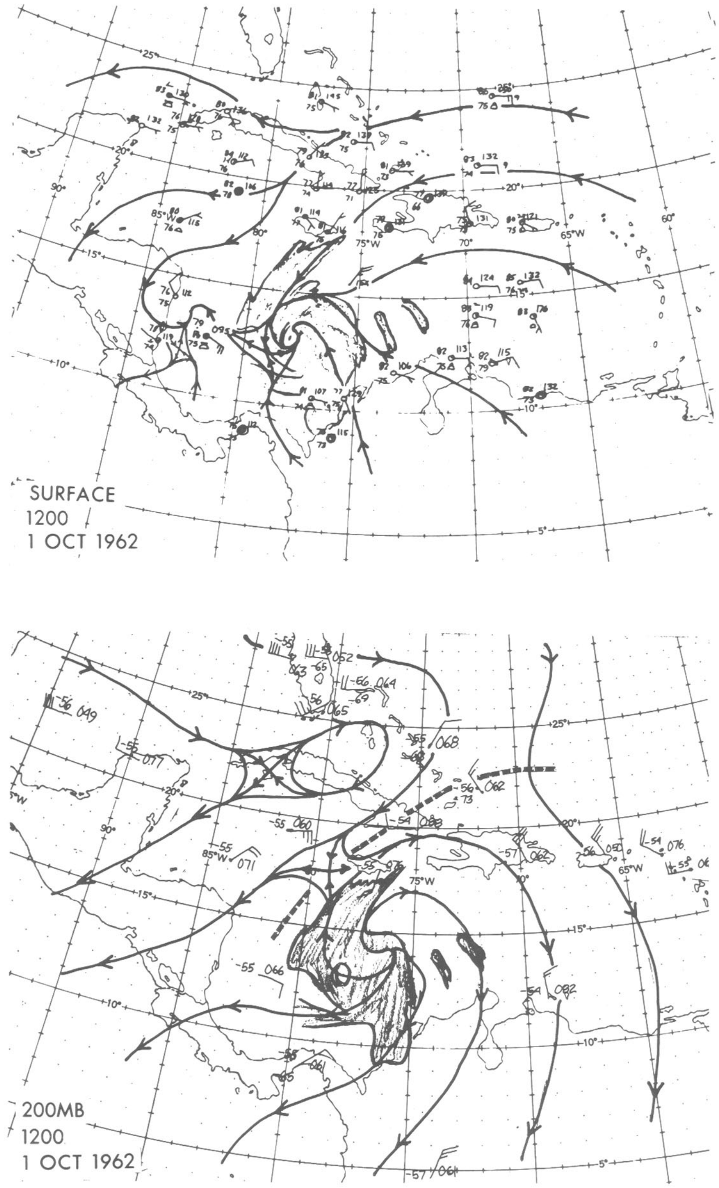

FIGURE 5.—The surface and 200-mb. streamline analyses over the Caribbean for 1200 GMT, October 1, 1962. Shading shows the area of cloudiness.

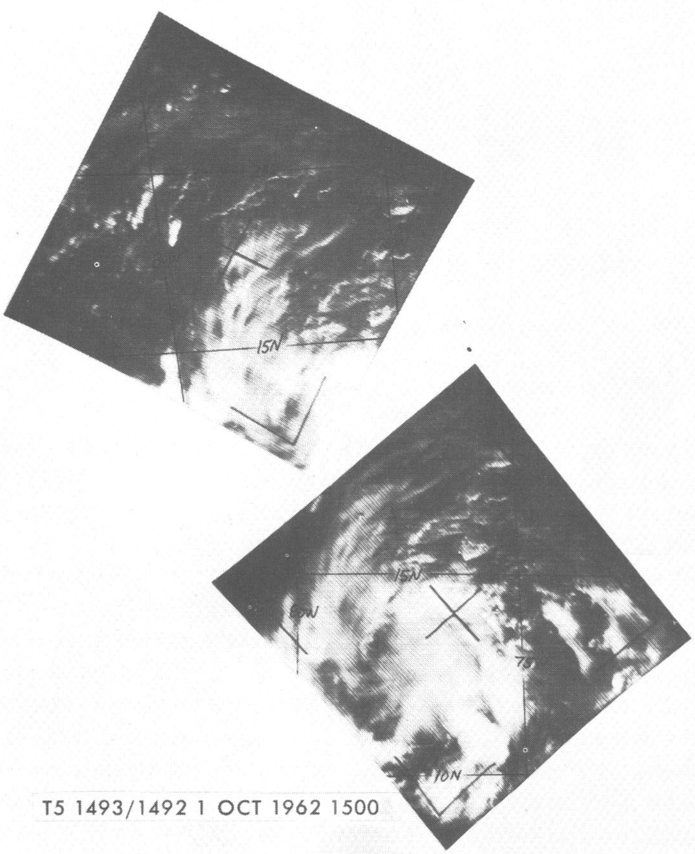

FIGURE 4.—TIROS V views of the Guatemalan storm at 1500 GMT, October 1, 1962.

3. FORMATIVE STAGE OF HURRICANE ALMA, AUGUST 1962

On August 23, 1962, TIROS V obtained a view of the wave destined to develop into hurricane Alma. The photographs in figure 7 show weak low-level banding, suggesting a center of circulation along the western edge of the disturbance near 16° N., 73° W. This disturbance would be classified as Stage B in Fett's scheme (figs. 1 and 2). The center, indicating a closed circulation relative to the moving storm, need not be reflected as a closed center in a coordinate system fixed to the earth. Surface

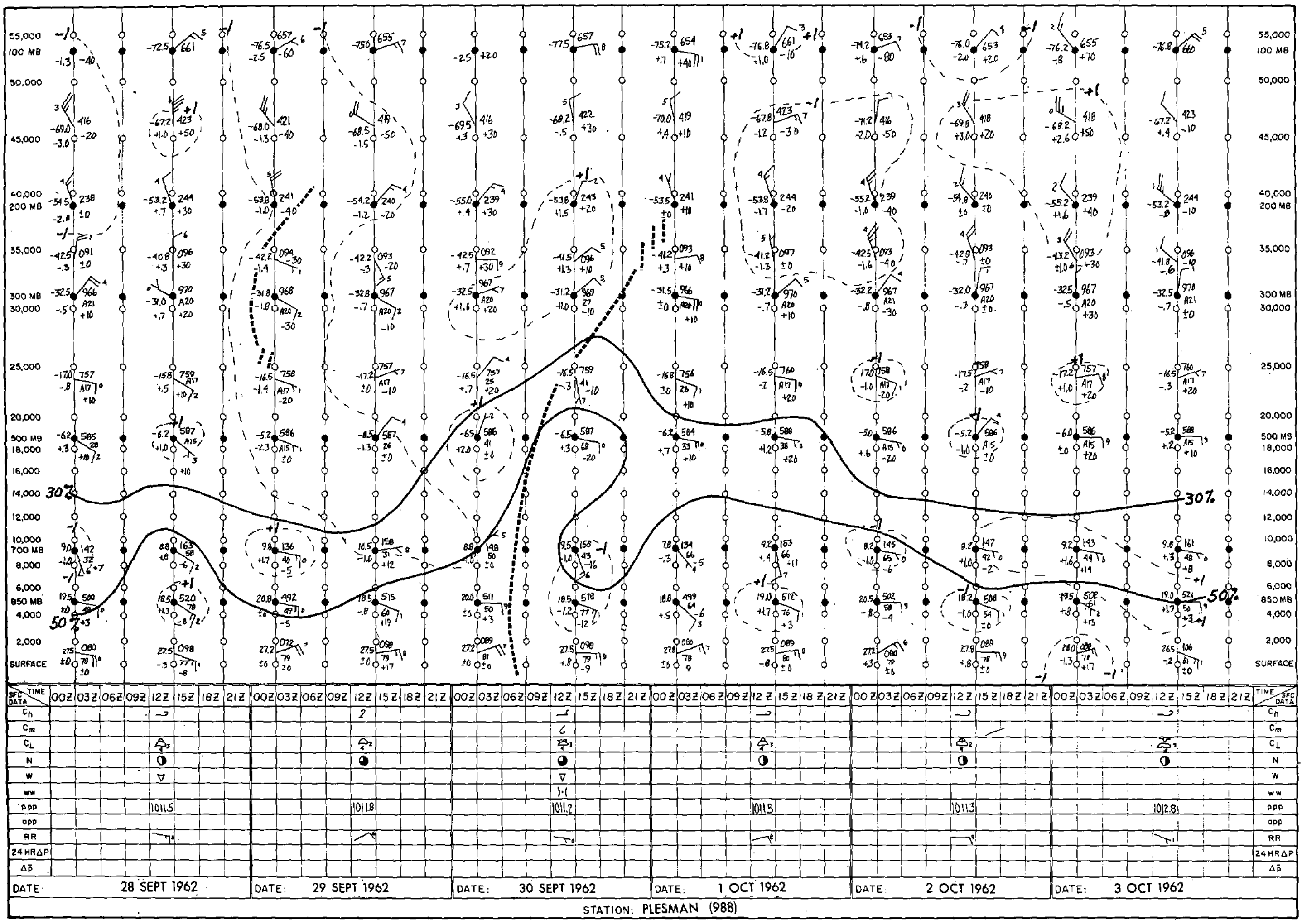

FIGURE 6.—A time-section for Plesman, Curaçao (approx. 12°N., 69°W.) for the period September 28 through October 3, 1962. 24-hr. temperature changes are plotted in the middle of the preceding 24-hr. period and the field is analyzed (dashed lines). Trough positions are indicated by heavy dashed lines and the relative humidity field is analyzed (solid lines).

reports were adequate to define a wave south of Hispaniola preceded by a sharp surface ridge (fig. 8). Wind speeds were light near the center of circulation, or along the wave axis, but increased to 30 kt. in the convective cloudiness to the east. Aloft an almost complete phase reversal is evident (fig. 8). A very sharp shear line overlay the surface ridge, and an anticyclone was superimposed over the convective cloudiness east of the surface trough. Note that the relatively clear conditions over the eastern tip of Cuba (fig. 7) were directly under the shear line at 200 mb. in figure 8. Typically, air within shear lines such as this is dry and subsiding [7]. Thus, upper-level convergence, subsidence, and lower-level divergence are suggested in or under the shear zone. The cloudiness in the disturbed area suggests lower-level convergence, upward vertical motion, and upper-level divergence.

The TIROS photographs, and the surface and upper-air analyses of figures 7 and 8 support this argument, and a space-section demonstrating conditions 4 hr. prior to the TIROS pictures is additionally revealing (fig. 9). Of dominant interest is the shear line at upper levels located between Grand Cayman (Station 383, near 14.5° N., 81.5° W.) and Guantanamo (Station 367, near 20° N., 75° W.). The shear line was quite intense in the layer 200–300 mb. but generally weakened at lower levels, and it finally disappeared near the 500-mb. level. The humidity analysis reveals that the air was very dry under the trough, but that the depth of the moist layer increased abruptly in the wave pattern between Santo Domingo (Station 486, near 13.5° N., 70° W.) and San Juan (Station 526, near 13.5° N., 66° W.). Positive 24-hr. height changes (not shown) and warming occurred in the mid-troposphere under the trough, while at the surface

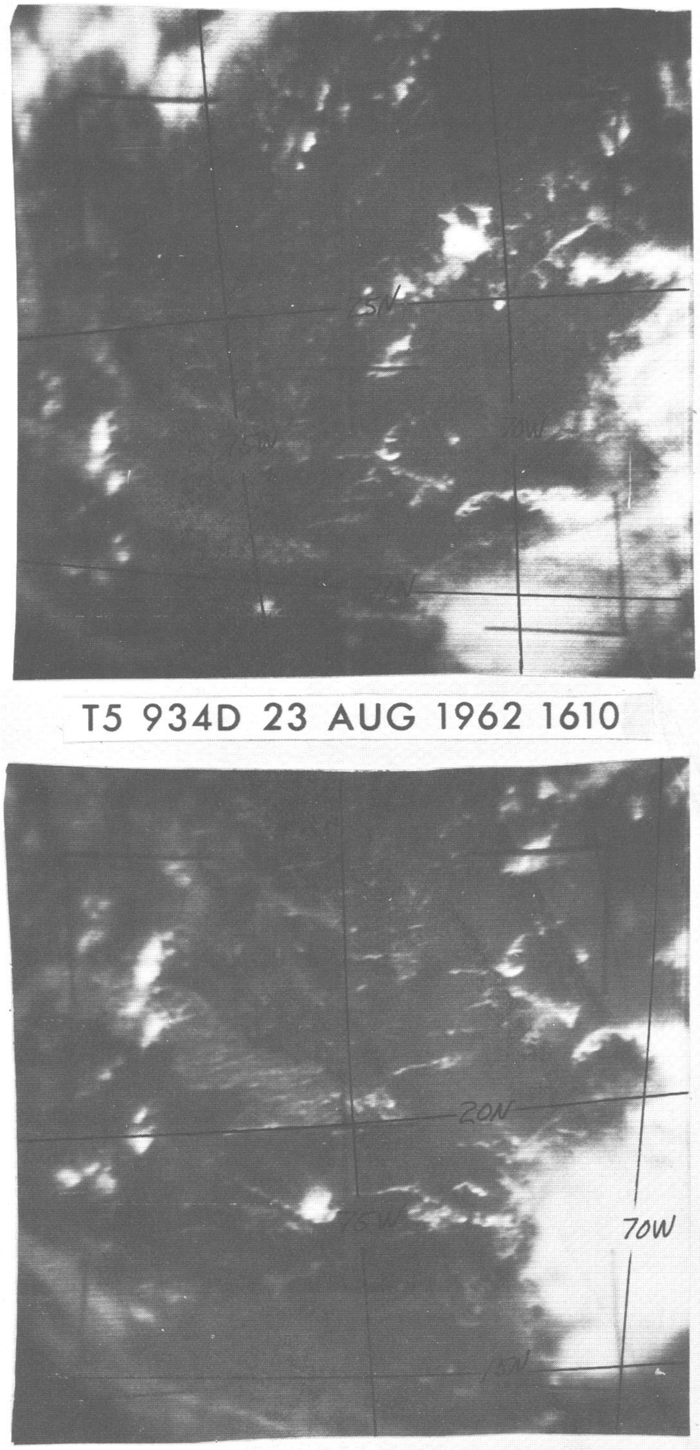

FIGURE 7.—TIROS V pictures of a formative stage of hurricane Alma, 1610 GMT August 23, 1962. Cuba and the western peninsulas of Hispaniola are clearly visible.

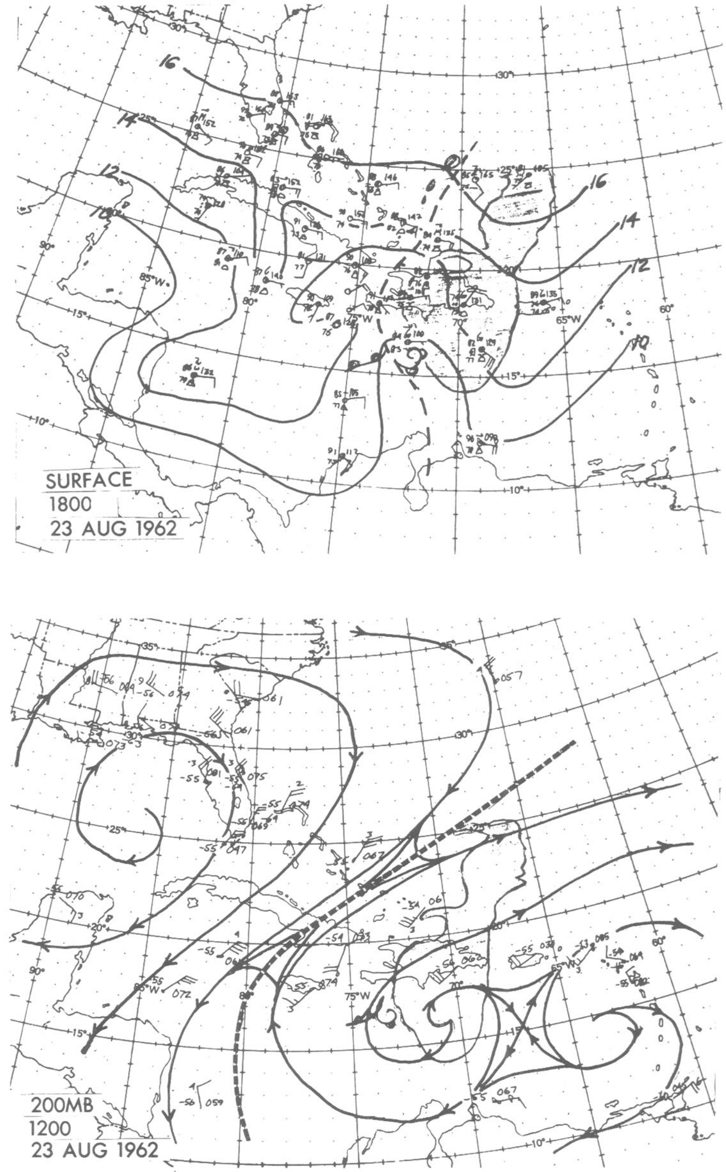

FIGURE 8.—Surface (1800 GMT) and 200-mb. (1200 GMT) analyses for August 23, 1962.

the 24-hr. pressure changes were negative. This pattern suggests pronounced subsidence and is in accord with the suppressed cloudiness conditions reported at Kingston (Station 397, near 13° N., 67° W.) and Guantanamo. The surface trough or easterly wave sloped eastward toward the colder air behind the trough axis and intersected middle levels at entirely different positions than did the upper trough. At 200 mb. the anticyclonic turning of the wind over the disturbance is well revealed by the shift from SSW at Guantanamo to NW at Guadeloupe (Station 897, near 16.5° N., 61.5° W.).

4. FORMATIVE STAGE OF TYPHOON BESS, JULY 1963

TIROS VII photographs on July 25, 1963 provide an excellent view of a formative stage of typhoon Bess. Figure 10 is a mosaic and nephanalysis of the pictures obtained. The elongation of convective cloudiness from

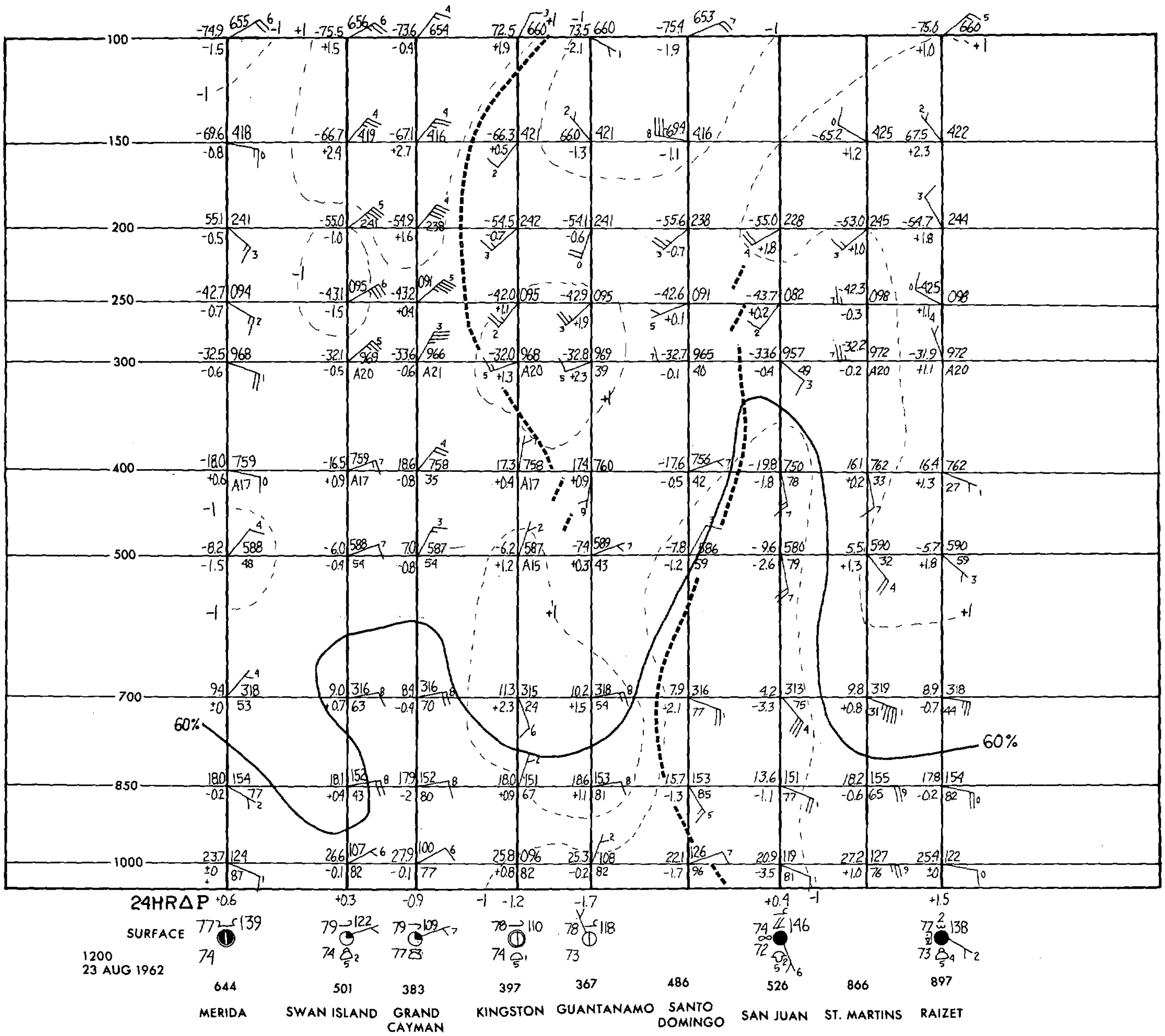

FIGURE 9.—A space-section for August 23, 1962, at 1200 GMT. Trough lines are indicated as heavy dashed lines. 24-hr. temperature changes are plotted in the middle of the preceding 24-hr. period. The 24-hr. temperature changes (light dashed lines) and relative humidity field (solid lines) are analyzed.

the equator to 15° N. suggests an easterly wave pattern with axis along the western boundary of major cloudiness. Weak low-level banding and a comma-like shape of the western boundary of the bright cloud-mass between 5° and 10° N. indicate that this depression should be categorized as Stage B (figs. 1 and 2). The depression had been tracked for two days previous in the analyses of the Fleet Weather Central, Guam (Station 217, near 13.5° N., 145° E.). A space-section (fig. 11) 6 hr. after the TIROS photographs reveals features very similar to those noted in the previous analyses. The upper shear line located between Guam and Truk (Station 334, near 7.5° N., 152° E.) was again related to warm, dry, subsiding air in advance of the low-level trough. The shear line cannot be traced below the 300-mb. level. The low-level trough sloped eastward with height toward lower temperatures in agreement with the classical model. The marked increase in depth of the moist layer in the area of the low-level trough compared with that under the upper trough is notable. Anticyclonic turning of the

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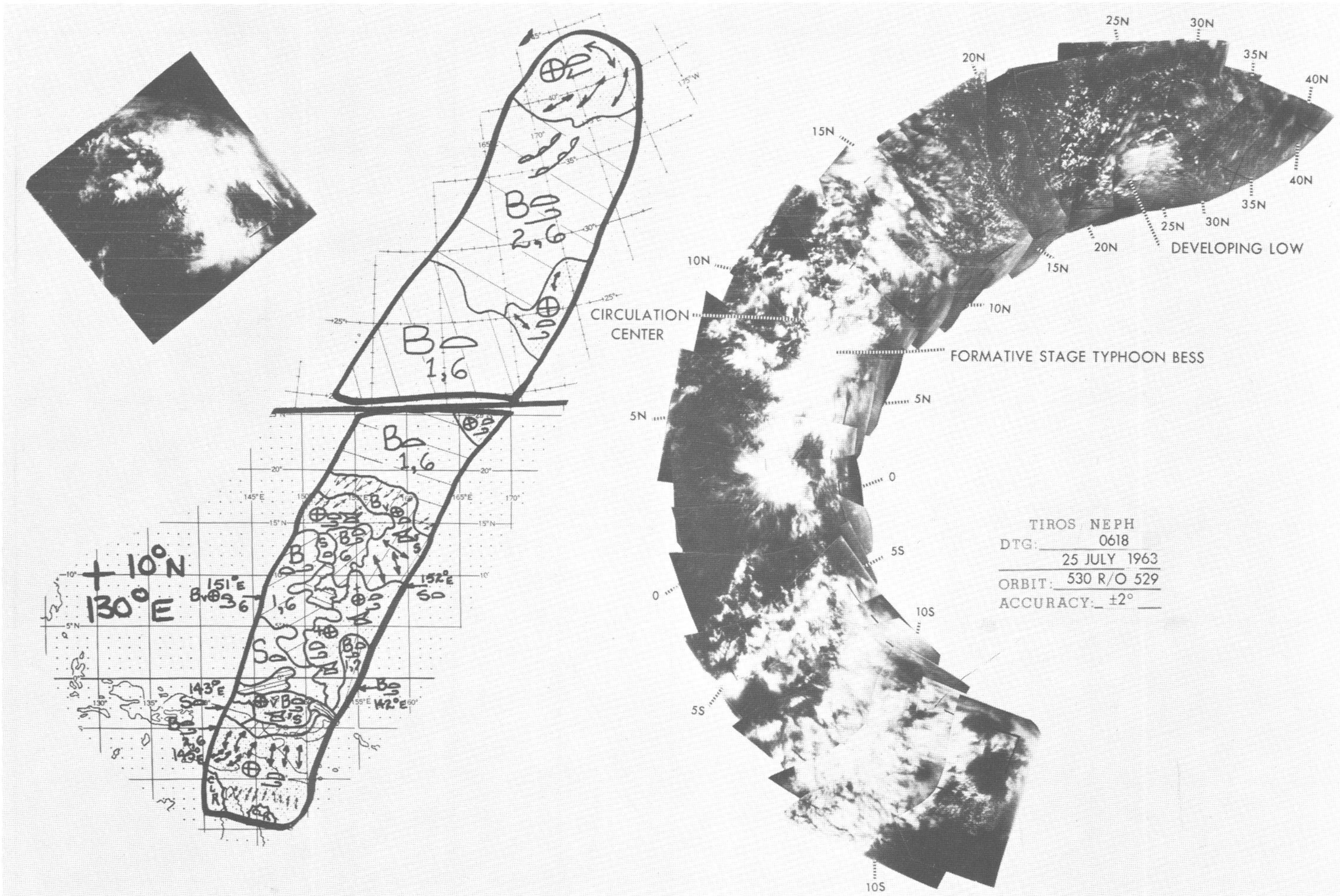

FIGURE 10.—A mosaic and nephanalysis of a TIROS VII pass over the formative stage of typhoon Bess, 0618 GMT July 25, 1962.

winds over the depression is evident at the 200-mb. level from Ponope (Station 348, near 7° N. 158° E.) to Kwajalein (Station 366, near 8.5° N., 167.5° E.) and it is also suggested in the cirrus striations visible in the TIROS photos.

5. PHYSICAL CONSIDERATIONS

Vorticity considerations as discussed by Riehl ([8], p. 219–223) may be used to explain the lower-level convergent conditions east of the wave axis which in turn gives rise to the convection found in these same areas. This accounts for the patterns of cloudiness viewed by TIROS and depicted in figure 1. This cloudiness distribution is anticipated when the speed of the easterly current exceeds the speed of the wave in the manner most commonly found. Yanai [10] has discussed the necessity for having an upper anticyclone over the easterly wave in order to have typhoon formation. In 17 wave examples Yanai found only 2 that were not characterized by anticyclonic vorticity aloft. In every wave that developed the upper anticyclone was also accompanied by warming as evidenced by positive 400-mb. temperature anomalies. However, on the basis of his data, Yanai could not conclude that the upper anticyclone and upper warming were dependent phenomena. The present study tends to indicate that this is indeed the case. Areas of enhanced and prospering convective activity, in the examples considered, inevitably appeared to be characterized by anticyclonic conditions aloft. The fact that the ridges or anticyclones were centered over the areas of strongest convection and that they remained in these positions as the waves progressed from day to day is the strongest evidence that these features were not the result of chance migration but, rather, the forced result of internal heat released through convection.

Low-level divergence in advance of the wave axis is predicted by vorticity considerations, and the subsidence from higher levels which this engenders is extremely well related in theory to the location of a convergent shear zone aloft over the same area. In fact, it has been argued a "reversal of the low level convergence and divergence patterns with height . . ." in association with an easterly wave "is always necessary if the surface pressure pattern is to change very little, yet appreciable bad weather . . ."

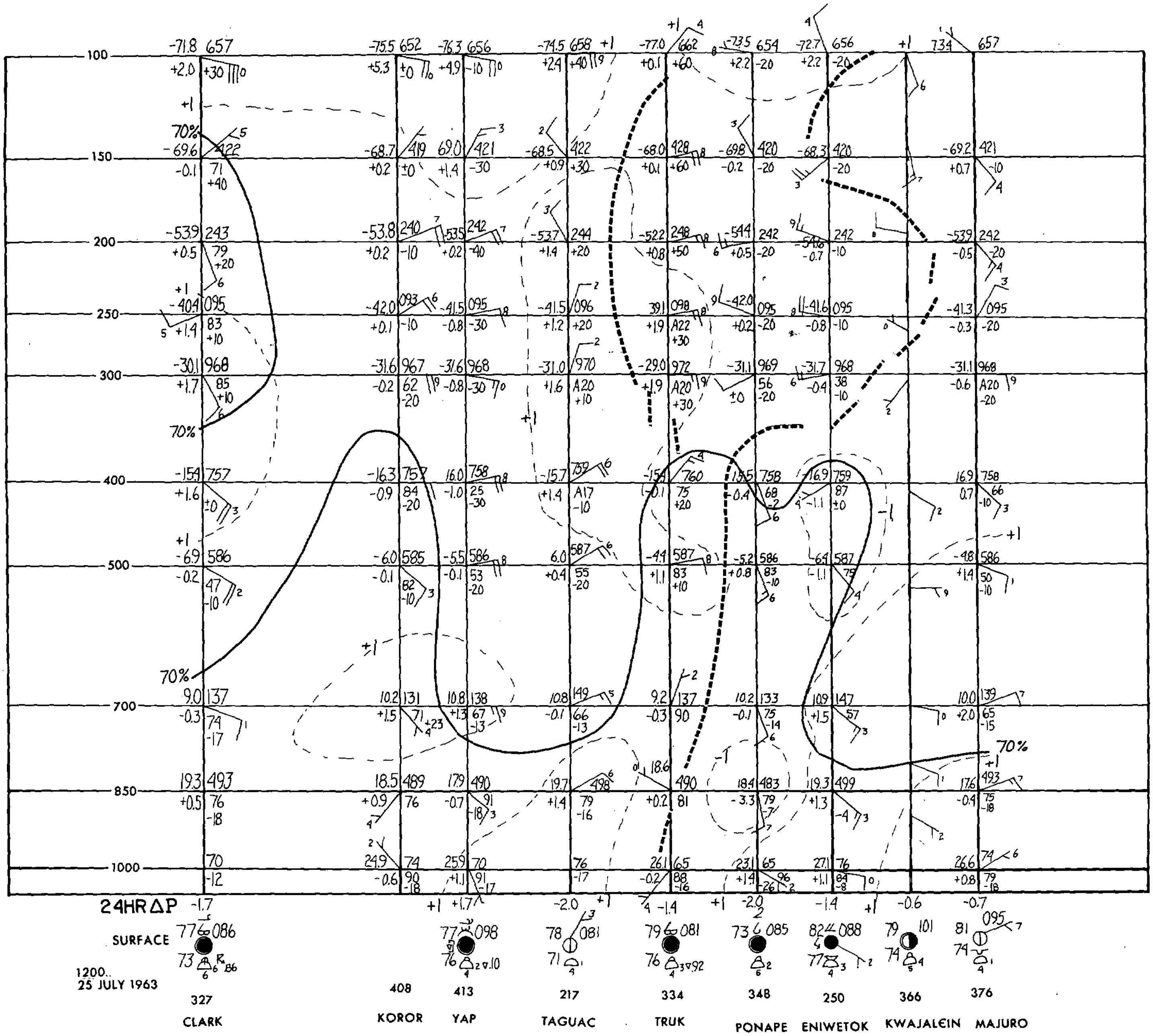

FIGURE 11.—A space-section for July 25, 1962 at 1200 GMT. Trough lines are indicated as heavy dashed lines. 24-hr. temperature changes, plotted in the middle of the preceding 24-hr. period, are analyzed by light dashed lines. The relative humidity field is shown by the solid lines.

results ([8], p. 221). In the weaker disturbances anticyclonically turning westerly winds (but no closed Highs) were most frequently found over the wave-associated areas of enhanced convection. Advance upper-level troughs were nearly always found preceding the ridges in the better developed examples. This configuration is typical of Stages A and B (figs. 1 and 2) and is descriptive of the configuration of the early stage of typhoon Bess shown in figure 10. Data indicate that as the wave intensified an upper anticyclone formed out of the ridge over the convective area, and the upper-level trough was observed to assume the characteristics of a shear line. The convergent nature of the upper-level shear line is implied by the TIROS photographs which show minimum cloud cover in the shear line area on a continuing basis. This configuration is most typical of Stages C+ and D (figs. 1 and 2).

Finally, in reviews of the TIROS histories of disturbances which attained tropical storm intensity or greater an obvious observation has been that prior to intensification organized convection has always been observed. The present study has been limited to those examples which depict a condition of enhanced convection. Thus, the weaker category of easterly wave with little developed convection has not been considered. In the light of the preceding discussion there is little reason to conclude that a characteristic upper-level pattern could be found over these weaker categories. It also appears that the meteorological satellite is an ideal tool for distinguishing between the weaker waves and those of a more intense character.

6. SUMMARY

The classical easterly wave model, which can include embedded vortices, is extremely well related to the observations obtained by satellite. The most commonly observed structure, however, indicates that there exists a favored pattern at upper levels where an approximate phase reversal from the low-level pressure pattern can be found. This upper-level structure has not been stressed in the literature to date. Thus, upper-level troughs or shear lines appear to overlie the ridge lines preceding low-level troughs, and upper-level ridges or anticyclones are normally found just east of the low-level trough positions in the areas of enhanced convection. The upper-level trough decreases in intensity downward and the lower-level trough decreases in intensity upward. The sample of cyclones from which these conclusions were drawn all were typified by developed convection, and thus these conclusions strictly pertain to cyclones of moderate intensity or greater.

ACKNOWLEDGMENTS

The author is indebted to A/1C Thomas F. Hayes for assistance in the preparation of data gathered in this study and to Dr. William M. Gray for helpful suggestions and an exceedingly valuable critique.

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[Received July 21, 1965; revised September 22, 1965]